ONR Final Technical Report

Contract Number	N000141-01-06-9-9
Title of Research	DURIP: A Confocal Imaging System for Ultra-Fast Three-Dimensional Transport Studies in Thermal Management Applications
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Organization	MIT

Abstract

We developed a new integrated imaging system, comprised of the requested confocal microscope and high-sensitivity camera, as well as our own state-of-the-art high-speed and high-resolution cameras, to achieve diffraction-limited 3D imaging of highly transient flows. The confocal incorporates selectable pinholes to enable fast scanning, and when interfaced with a high-speed camera, can achieve capture rates up to 1000 Hz. The combination of these features offers drastic improvements to our existing imaging systems, which are limited in spatial and/or temporal resolution. The proposed system enables fundamental insights into our ongoing thermal management efforts focused on i) Interfacial dynamics on nanostructured surfaces, ii) Phase-change and flow through porous media, and iii) 3D velocity field measurements in microscale systems. The integrated confocal microscope system is a critical component to obtain understanding of fluid-heat-structure interactions, as well as offer design guidelines for the development of high-performance thermal management systems.

Technical Objectives

The objective of this work was to develop a high speed three-dimensional (3D) confocal imaging system to study coupled fluidic and heat transport processes for high-performance thermal management applications. Thermal management is a critical bottleneck for the advancement of important defense systems, such as phased-array radars, high band-width jammers, and microwave and digital electronics. However, to successfully implement these approaches, we seek fundamental understanding of interfacial dynamics and transport processes. The integrated imaging system, comprised of the requested swept-field confocal microscope and high-sensitivity camera, as well as our own state-of-the-art high-speed and high-resolution cameras, achieve diffraction-limited 3D imaging of highly transient flows. The laser confocal scanner with selectable pinholes enables fast scanning, and when interfaced with a

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high-speed camera, achieves capture rates up to 1000 Hz. The combination of these features offers drastic improvements to our existing imaging systems, which are limited in spatial and/or temporal resolution. The system enables fundamental insights into our ongoing thermal management efforts focused on i) Interfacial dynamics on nanostructured surfaces, ii) Phase-change and flow through porous media, and iii) 3D velocity field measurements in microscale systems. The equipment is a critical component to obtain understanding of fluid-heat-structure interactions, as well as offer design guidelines for the development of high-performance thermal management systems.

Technical Approach

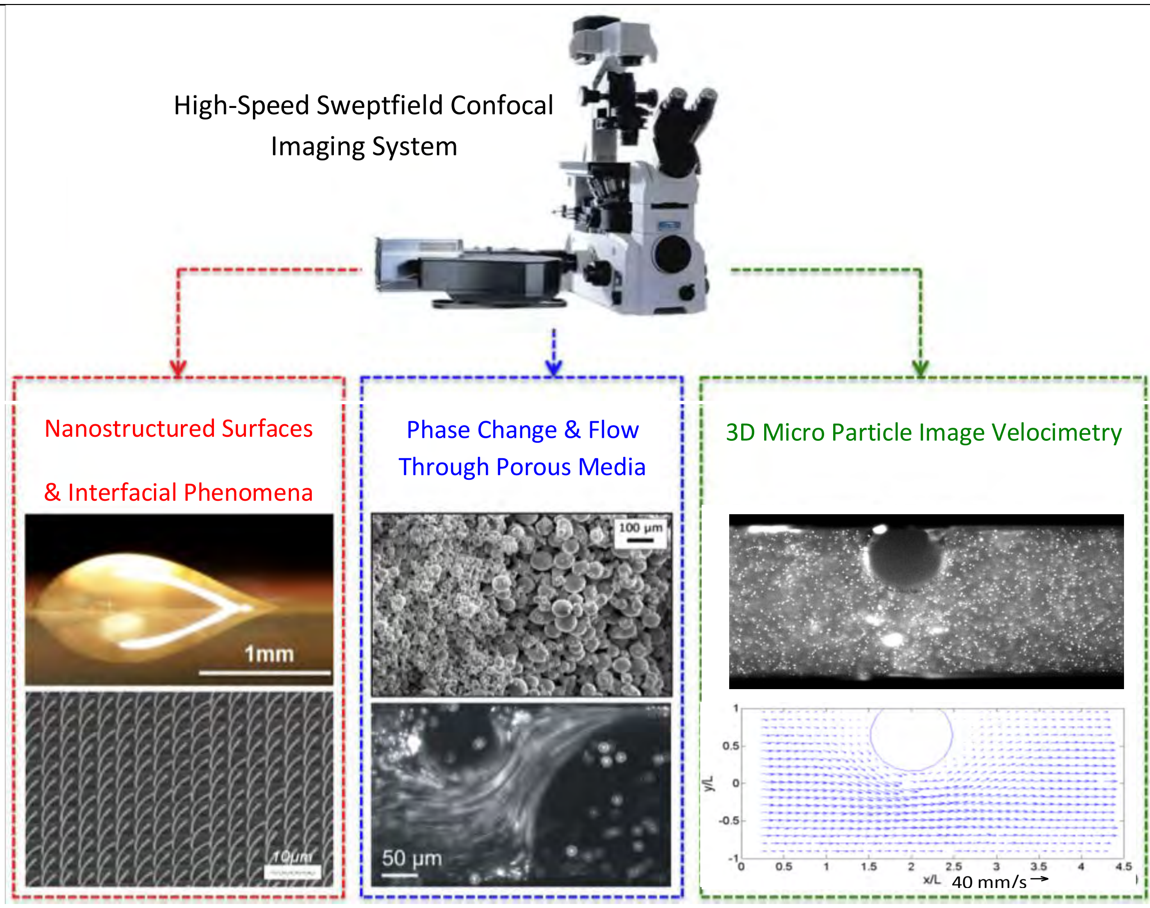

Fig. 1: High-speed confocal imaging system for the investigation of fundamental thermal, fluidic, and interfacial phenomena at the microscale.

The quantitative high-speed diffraction-limited confocal imaging system is aimed to achieve new insights into complex liquid-heat-structure interactions and interfacial phenomena (Figure 1). A key component to achieving highly resolved transient flows and interfacial dynamics is the requested laser confocal scanner with selectable pinholes combined with either one of our existing state-of-the-art cameras or the requested high-sensitivity camera. The integration of these components enables imaging of ultra-fast 2D flow phenomena at rates up to 1000 Hz or 3D flow phenomena down to the diffraction limit (~200 nm) at rates of approximately 100 Hz. This important instrumentation enables fundamental studies to investigate:

i) Interfacial dynamics on nanostructured surfaces. The confocal system will enable high accuracy measurements of liquid film thickness, and will resolve the 3D shape of the liquid-vapor/air meniscus during liquid propagation, evaporation, and bubble nucleation. This work has potential applications in controlling thin film evaporation and bubble removal processes on demand.

ii) Phase-change and flow through porous media. The confocal system will enable extracting contact angles during evaporation and condensation on microstructured wicks. This work has potential impact in novel heat pipe designs, which can be integrated into high performance air-cooled heat exchangers.

iii) 3D velocity field measurements in microscale systems. The confocal system will enable quantitative velocity field data in highly transient flows. This can be applied to studies described in i) and ii), as well as other micro-/nanofluidic geometries.

We have successfully developed the high-speed diffraction-limited confocal imaging system. Furthermore, we demonstrated important functionality of the system to study interfacial phenomena on nanostructured surfaces. Specifically, we used the confocal microscope system to experimentally capture the three-dimensional shape of the meniscus in pillar arrays. Such quantitative understanding is essential to accurately obtaining the capillary pressure and liquid propagation rates. Second, we were able to obtain the shape of the liquid front during liquid propagation in pillar arrays, which determines the local pressure gradient. This understanding helped explain the role of microscopic dynamics in macroscopic propagation rates. Finally, the confocal microscope facilitated understanding of how microstructures can be used to pin the liquid. This is a first step towards developing methods to quantifying thermal interfacial resistances. These measurements offer new insights towards understanding fluid-thermal-structure interactions to aid in the development of high heat flux thermal management solutions.

Technical Outcomes

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1) Integrated High-speed Diffraction-limited Confocal Imaging System

We procured and integrated the high-speed confocal imaging system which is comprised of a Visitech-Infinity3 Multi-beam laser confocal scanner with selectable pinholes, two solid state lasers, a Hamamatsu EMCCD high-sensitivity camera, and a Nikon upright microscope. Together, they enable state-of-the-art temporal and spatial resolutions, with 2D and 3D capture rates of 1000 Hz and 100 Hz, respectively, down to sub-micron spatial resolutions. The modular system can also be easily integrated with two cameras previously purchased through existing DoD grants (Phantom v7.1 and CoolSNAP HQ). The confocal system's modular design allows for easy integration with a variety of cameras and lasers, to achieve the ideal optimizations of combined spatial and temporal resolution, and sensitivity. The confocal system operates in both fluorescence and reflective modes and has the potential for unprecedented flow imaging capabilities through a variety of integrated components. Our recent efforts have focused on using the confocal microscope system with a 405 nm and 532 nm solid state laser to investigate interfacial phenomena and quantify meniscus shapes to predict liquid propagation behavior on engineered surfaces.

2) Interfacial Measurements of Liquid Film Thickness and Meniscus Shape

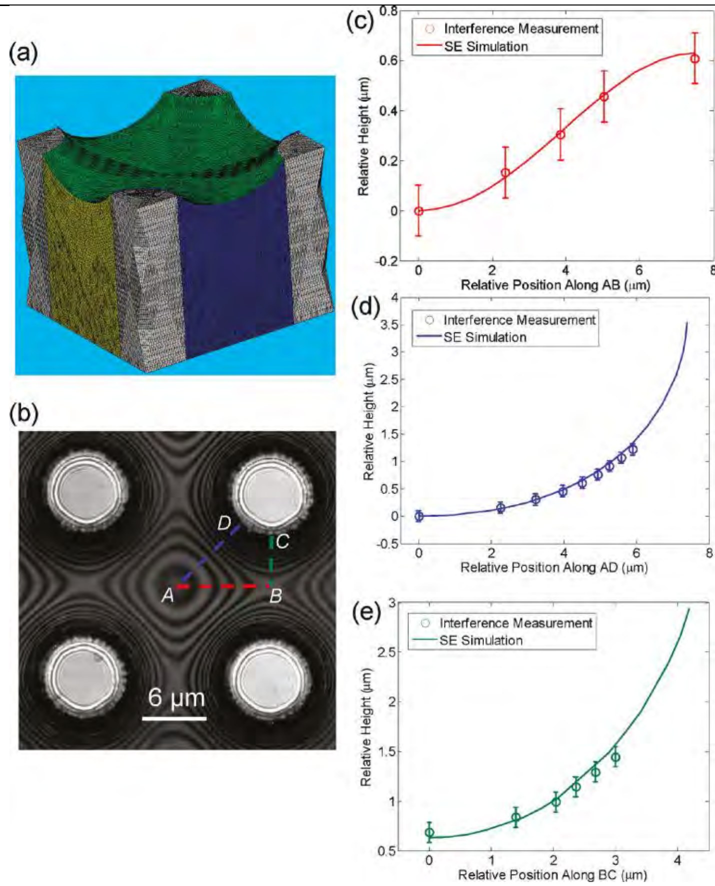

Fig. 2: Comparison of the water meniscus shape from simulation and experiment. (a) Simulated meniscus shape using Surface Evolver (SE) where d = 6.4 μm and l = 15 μm. (b) Image of the water meniscus obtained using confocal microscopy system in the same micropillar array as (a). Each dark fringe corresponds to $\lambda/2n$ (λ=405 nm is the wavelength of the laser and n = 1.3 is the refractive index of water) in the relative thickness of the liquid film. Comparisons of the simulated and measured meniscus along (c) the red line, AB, (d) the blue line, AD, and (e) the green line, BC. The ordinates correspond to heights relative to point A.

Prediction and optimization of liquid propagation rates in micropillar arrays are important for various thermal management applications. To develop a model to predict liquid propagation rates requires quantifying the capillary pressure, where understanding the meniscus shape is essential. We used the confocal microscope system to measure the meniscus shape in the pillar array. Fringes are generated by the interference of laser light (λ = 405 nm) reflected at the liquid surface and at the substrate. The shape of the water meniscus in the pillar arrays are obtained by examining the dark fringes, where each dark fringe corresponds to a $\lambda/2n$ difference in the relative thickness of the liquid film, where n = 1.3 is the refractive index of water. In addition to the measurements, we used Surface Evolver simulations to corroborate the experiments.

Figure 2 compares the simulated meniscus shape to experimental confocal microscope system measurements on a micropillar array with diameter d = 6.4 μm and period l = 15 μm. Fig. 2(a) shows the three-dimensional meniscus shape obtained by SE and Fig. 2(b) shows the top-down view of the experimentally obtained interference patterns on the same pillar geometry. Close to the pillar sidewalls (< 1 μm), accurate data was difficult to obtain due to refraction. Fig. 2(c)-(e) compare the meniscus shape predicted by simulation and obtained experimentally along the horizontal (AB), diagonal (AD), and vertical (BC) directions, respectively. The error bars in the data were determined based on the width of the dark fringes. The experimental results were well-predicted by the simulation. Experimental measurements on additional geometries with d =2.5 μm - 6.4 μm and l = 8 μm – 30 μm were performed and exhibit similar agreement.

The confocal microscope system was also used to quantify the meniscus of the liquid front during propagation in micropillar arrays. Such information is important to understand how microscopic dynamics affects macroscopic propagation rates, where the shape of the liquid front determines the local pressure gradient. Fig. 3(a) shows a representative interference pattern of the liquid front on a pillar array with d = 5.9 μm, l = 15 μm, and h = 3 μm acquired by a confocal microscope system with a laser source (λ = 532 nm). Each dark fringe corresponds to a $\lambda/2n$ difference in the thickness of the liquid, where n is the index of refraction of the liquid (n = 1.33 for water). The meniscus profiles along two different locations, *AB* and *A'B'* in Fig. 3(a), are shown in Fig. 3(b). This information was essential to predict the local propagation rate within the pillar array.

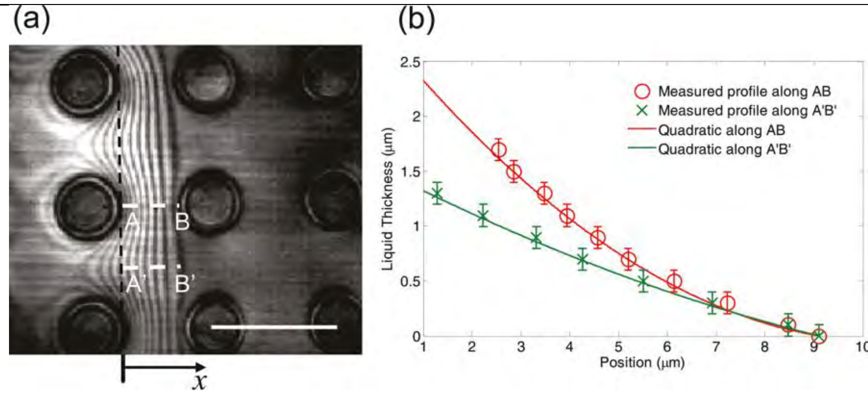

Fig. 3: (a) Liquid meniscus sweeping between pillars obtained with the confocal microscope system (laser wavelength λ=532 nm). The diameter, period, and height of the pillar array are d = 5.1 µm, l = 15 µm, and h = 3 µm, respectively. Each dark fringe corresponds to a $\lambda/2n$ difference in the liquid thickness. Scale bar is 15 µm. (b) Measured meniscus profiles along two locations, AB and A'B'. The profiles are well-captured by quadratic functions at both locations. Error bars were defined by the maximum possible height difference within one dark fringe ($\lambda/2n$).

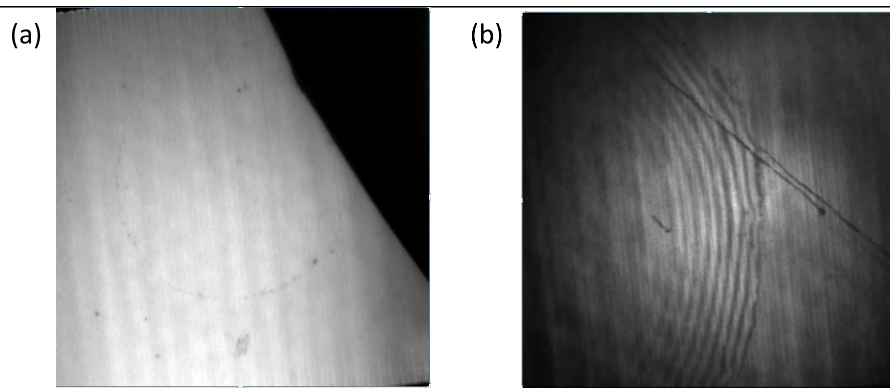

Fig. 4: Confocal microscope images of the evaporating water contact line (a) without pinning and (b) with pinning on the Pyrex microstructures.

Evaporation from the thin film regions of water is gaining significant interest in the scientific community with the potential application in providing active cooling solutions for the microelectronic devices. We studied evaporation of the water droplets on a micro-patterned Pyrex structure using the confocal microscope system. The micro-patterned sample consisted of a periodic array of 100 µm diameter and 400 nm deep holes that were etched onto a Pyrex wafer. The distance between the centers of any two neighboring holes was 300 µm. Our calculations showed that by increasing the apparent contact area (or surface roughness) in this manner would help promote the water contact line pinning around the edges of these micro-patterned holes. We conducted a series of experiments where we placed water drops that were much larger than the size of the etched holes on the micro-patterned sample and allowed them to evaporate in ambient condition. We employed the confocal microscope to capture the evaporation process in real-time. The evaporating water drops displayed two distinct trends:

1) When the size of the evaporating drop was much larger than the size of the holes, the evaporating water contact line did not adhere on the periphery of the holes (Fig. 4a), i.e., no fringe patterns.
2) When the size of the evaporating water drop becomes smaller and comparable to the size of the holes, the evaporating water contact line started to pin around the edge of the hole (Fig. 4b). We also observed that the evaporation process slowed down after the contact line pinning, i.e., fringe patterns.

The confocal microscope system has elucidated the effect of the microstructures on contact line pinning. This is essential for the next step in quantifying thermal interfacial resistances.

Refereed Journal Article

1. Xiao, R., Enright, R., and E.N. Wang, “Prediction and Optimization of Liquid Propagation in Micropillar Arrays,” Langmuir, 26 (19), 15070-15075, 2010.

2. Xiao, R., and E.N. Wang, “Effect of Microscale Liquid Dynamics on Macroscale Propagation in Pillar Arrays” Langmuir, la202206p, 2011.

Presentations

Proceedings

1. Wang, E.N., Xiao, R., and K.-H., Chu, “Nanoengineered Surfaces: Transport Phenomena and Thermal Management Applications,” Proceedings of the XXVIII UIT Heat Transfer Conference, Brescia, Italy, June 21-23, 2010. (Invited keynote)

2. Wang, E.N., Xiao, R., K.-H., Chu, and R. Enright, “Nanoengineered Surfaces for Efficient Energy Systems,” Proceedings of the ASME 2011 9th International Conference on Nanochannels, Microchannels, and Minichannels, Edmonton, Alberta, Canada, June 19-22, 2011. (Invited keynote)

Presentations only

1. Xiao, R. Enright, R., and E.N. Wang, “Dynamics of Liquid Meniscus in Micropillar Arrays,” 63rd Annual Meeting of the APS Division of Fluid Dynamics, November 2010.

2. Shukla, N., Milkjovic, N. Enright, R., and E.N. Wang, “Thermal Resistance of Thin Water Films During Phase-change.” American Physical Society, Spring, March 2011.

3. E.N. Wang, “Nanoengineered Surfaces for Microfluidics and Energy Systems.” Ontario-on-a-Chip, Toronto, CA, June 2011 (Invited keynote).